RESERVE CCPY

PATENT SPECIFICATION

DRAWINGS ATTACHED

1,175,091

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International Classificaton:—H 01 v 11/06.

COMPLETE SPECIFICATION

Superconducting Apparatus

We, FORD MOTOR COMPANY, of the American Road, Dearborn, Michigan, United States of America, a Company incorporated in and according to the Laws of the State of Delaware, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to apparatus using superconductive devices.

According to the invention we provide apparatus in which:

(a) a device is located in a cryogenic environment to render the device superconducting;

(b) the device comprises a closed superconducting loop which includes at least one weak link (as hereinafter defined);

(c) there are no direct electrical connections to the device;

(d) an input circuit inductively coupled to the device induces varying currents in the device of amplitude limited by the critical current of the weak link; and

(e) the varying currents in the device induce output signals in an output circuit inductively coupled to the device.

The term "weak link" is used in this specification and in the appended claims to define a junction between two superconductive elements which is superconductive for small currents flowing through the junction but is conventionally conductive, with a finite resistance, when a critical current (I_c) of the weak link is exceeded, the two superconductive elements themselves remaining super-conductive when this critical current is exceeded.

How the invention may be carried out will now be described with reference to the accompanying drawings in which:—

Figure 1 is an exploded view of the parts of a superconductive quantum interference device;

Figure 2 is an end view, partially in section of the superconductive portion of the structure shown in Figure 1;

Figure 3 is a schematic representation of the superconductive quantum interference device and the adjacent coils;

Figure 4 is a series of curves demonstrating the operation of the invention;

Figure 5 is a graph of the effect of the applied field upon the flux in the superconductive quantum interference device;

Figure 6 is a graph of the superconductive quantum interference device current against the applied field for certain chosen values of I_c; and

Figure 7 is a schematic showing of a structure in which a single coil serves both as the input and output coil.

The preferred form of this superconductive quantum interference device is shown in Figure 2 and comprises two metal superconducting elements joined together to an insulating separator. This joint may be made by any suitable adhesive in the form of an insulating separator. Alternatively, the insulating separator may be a plastics material such as that available commercially as "Mylar" (Registered Trade Mark). The two superconducting elements unite to form a conduit in the form of a central passageway through the body of the superconductive quantum interference device. A suitable dimension for the outside diameter of the superconductive quantum interference device shown in Figure 2 as 1 cm.

Electrical contact is made between the two superconducting elements of the superconductive quantum interference device by means of two pointed cap screws that function as contact points (weak links) and are

[P. 1.]

received in suitable openings in one of the superconducting elements. The sharpened ends of the cap screws penetrate the insulation between the two superconducting elements permitting the flow of electrical current. By the adjustment of these two cap screws, the maximum supercurrent through the superconductive quantum interference device can be regulated. The significance of this supercurrent will be explained below.

The two superconducting elements and the cap screws are fabricated from metal capable of becoming superconductive at low temperature. These metals are well known. In the actual construction of the working superconductive quantum interference device, vanadium was employed as the two superconducting elements and the cap screws were niobium, although this invention is by no means so limited.

An example of one form of superconductive quantum interference device of Figure 2 can be seen in Figure 1. Suitable binding surrounds the superconducting elements to insure against separation. The superconductive quantum interference device is inserted in a cylindrical insulator. A hollow cylindrical container, having one portion thereof cut away, is adapted to receive the superconductive quantum interference device and cylindrical insulator. A suitable mounting is achieved by means of a strap partially surrounding the cylindrical insulator and attached to the container body by means of suitable fasteners.

Formed in the body of the container opposite the cut-away portion thereof is a slot of varying depth. Passageways are formed from this slot through the wall of the container to permit the passage of the pointed cap screws serving as contact points. A pair of female wrenches are mounted in the slot by means of suitable brackets and fasteners and are adapted to co-operate with the heads of the pointed cap screws. Formed integral with the shafts of these wrenches are worm gears. Longitudinal passageways are formed from the slot to one end wall of the container to permit the passage of adjusting shafts having worms formed near one end thereof. It may be seen that these worms co-operate with the worm gears so that rotation of the adjusting shafts will cause rotation of the pointed cap screws, thereby adjusting the electrical contact between the superconducting elements of the superconductive quantum interference device.

The superconductive quantum interference device may be assembled into working arrangement with input coils and output coils as shown in Figure 3. It will be readily apparent to those skilled in the art that neither the input coil nor the output coil need take the form shown in Figure 3. It is only necessary that the input coil and the output coil possess inductance and that they be magnetically adjacent the superconductive quantum interference device. Only the superconductive quantum interference device need be exposed to the cryogenic ambient necessary to render is superconductive. The input coil and output coil may be at any chosen temperature.

This invention is carried out by placing at least the superconductive quantum interference device in a cryogenic medium to render it superconductive and then placing an input coil and an output coil magnetically adjacent the superconductive quantum interference device. An alternating current I_i is now applied to the input coil.

Figure 4 shows the current that would flow in the various loops of this circuit if an alternating current I_i, were applied to the input loop coil. This current, Figure 4(a) would generate an alternating magnetic field, Figure 4(b), which would be applied to the superconductive quantum interference device. Since the superconductive quantum interference device is superconducting, a current is induced in it which generates a magnetic field equal and opposite to the applied field in order to maintain the flux threading through its central hole at a constant value. This induced current, shown in Figure 4(c), increases with the applied field until the critical current I_o, for the weak link is exceeded. At this current level, the weak link becomes a region of normal conduction and permits the passage of magnetic lines of force into the central hole of the superconductive quantum interference device thereby tending to equalize the applied field with the field within the superconductive quantum interference device.

Since quantum mechanics demands that changes in magnetic fields be carried out in units of the fundamental flux quantum (2.07×10^{-7} gauss cm^2), this adjustment of field between the inside and outside of the superconductive quantum interference device will continue until at least one flux quantum (2.07×10^{-7} gauss cm^2 times the superconductive quantum interference device hole area) has entered the superconductive quantum interference device. Once this is accomplished, the weak link becomes superconducting again and a superconducting current flows which is less than the critical value and keeps the inside of the superconductive quantum interference device shielded from the external field. As the external field continues to increase, this new current increases and if it reaches the critical value, another flux quantum can enter. Ordinarily only one flux quantum enters at a time, but jumps involving more than one have been observed in the laboratory. As the applied field decreases and reverses sign,

the current in the superconductive quantum interference device also decreases, reverses sign and reaches it critical value in the reverse direction. In this case, the magnetic flux will flow out of the superconductive quantum interference device. Each time there is a change in the flux through the superconductive quantum interference device, there is also a flux change in the pickup coil loop which is closely coupled to the superconductive quantum interference device. The voltage output from this pickup is $(d\Phi/dt)$ (N) (K) where $d\Phi/dt$ is the rate of flux change, N the number of turns in the pickup coil and K its coupling coefficient to the superconductive quantum interference device. The rate of the flux change $d\Phi/dt$ may be estimated by dividing the number of quantized flux units entering or leaving the superconductive quantum interference device in a half cycle of the current applied to the input loop divided by the time for a half cycle of input current; i.e., $2n\phi_0 f$ where f is the input frequency and n is the number of flux quanta entering or leaving the superconductive quantum interference device. If the output coil has an inductance L, then one can shunt it with a capacitor of capacity C such that $LC = (2\pi f)^{-2}$. This will increase the output voltage across the inductance at the frequency f by the quality factor Q of the LC combination. (The output voltage wave form shown in Figure 4(d) is for an output coil with a broad band, high frequency response). If this tuned frequency f is one of the harmonics in the Fourier expansion of the waveform in Figure 4(d), then the system pictured in Figure 3 can be considered as a harmonic generator with the property that the amplitude of a particular harmonic can be controlled not only by the choice of driving frequency but also by the amplitude of the applied current.

Another valuable property of this circuit shown in Figure 3 and the wave forms of Figure 4, is the hysteresis accompanying the flow of flux into and out of the superconductive quantum interference device. Figure 5 shows a graph of the flux in the superconductive quantum interference device hole as a function of the applied field. It can be seen that the flux in the superconductive quantum interference device hole at zero applied field is different depending upon the previous direction of the applied field. Thus the system can be used as a memory element in which different information is stored by applying either a positive or negative magnetic field pulse. This information can be read destructively by looking for a flux transition when a small "read" field of one particular sign is applied. A non-destructive read-out could be made with a separate superconductive quantum interference device which operates as a magnetometer and measures the flux stored in the memory superconductive quantum interference device.

The important element in Figure 3 is the superconductive quantum interference device. Its behaviour is controlled by three features:

1) The area of the central hole determines the over-all sensitivity because the interesting effects occur when the applied magnetic field multiplied by this area equals a flux quantum (2.07×10^{-7} gauss cm²). Thus effects will occur at ever decreasing applied fields as the central hole is made larger.

2) The critical current of the weak link determines the superconducting current at which a quantum transition will occur. This critical current can be controlled by the choice of several possible weak link construction methods which will be discussed later.

3) The change in critical current at a transition is approximately Φ_0/L where Φ_0 is the flux quantum and L the inductance of the superconductive quantum interference device. This current change is an amperes if MKS units are used. ($\Phi_0 = 2.1 \times 10^{-15}$ webers and L is in Henries.)

The case described in Figure 4 represents the situation in which the change in critical current (Φ_0/L) is smaller than the critical current which the weak link can support. Thus only a small fraction of the total current is changed at each transition and a considerable amount of hysteresis is introduced.

If the critical current becomes comparable to Φ_0/L, then the total current in the loop is greatly changed at a quantum transition and very little hysteresis occurs. This type of operation is described in Figure 6 where the current in the superconductive quantum interference device is plotted as a function of the applied field for the three cases (a) $2I_c > \Phi_0/L$, (b) $2I_c = \Phi_0/L$ and (c) $2I_c < \Phi_0/L$. (The characteristic curves given here are drawn as straight lines for simplicity of representation. In practice they may be curved depending on the detailed mechanical structure of the weak link.) Of these three characteristics the curve for $I_c = \Phi_0/2L$ is the most interesting because the change in superconductive quantum interference device current when the critical current is reached is most abrupt. This produces the most rapid flux change in the superconductive quantum interference device and in the pickup loop coil coupled to it.

All of the circuits described above have had separate coils for the input and output loops. Such an arrangement is not

necessary since one coil can be used for both purposes. Figure 7 shows schematic drawings of an amplifier and an oscillator using this method of construction. As in the embodiment of Figure 3, such a system also has the advantage that no electrical contact need be made to the superconductive quantum interference device itself. Thus the superconductive quantum interference device can be placed alone in its cryogenic environment while the coupling coils and associated electronics can be outside in the room environment. Usually, however, the coil and superconductive quantum interference device are together in the cryostat in order to have close coupling.

The construction of the superconductive quantum interference device itself is relatively straightforward. Any superconducting material can be used and the shape need only be such that it have an inductance. Usually a material with a high normal to superconducting transition temperature is preferable so that the device can be operated well away from its transition temperature in a conventional liquid helium bath. The effects of temperature on the operating characteristics of the device are expected to become important only very near the transition temperature.

The construction of the weak link is very important to the operating characteristics. Any of the following techniques can be used.

1) Josephson tunnelling films formed by evaporating or otherwise placing a thin film of an insulator between two superconductors. In such weak links, the critical current is determined by the insulating film thickness, its area of contact and the magnetic field that threads the junction itself. (Since these very thin films still have a finite area, the magnetic field which threads them can be important.) For this kind of weak link the current vs. applied field characteristic shown in Figure 6 will be curved instead of straight.

2) Small metallic bridges between the two superconductors formed by evaporating a superconducting metal film into small holes in an insulting film or by evaporating a superconducting film through a mask so that only a small neck is formed to connect two large evaporated superconducting films. For these evaporated bridges, the critical current is determined by the dimensions of the bridge and cannot be changed after the film is evaporated. Such bridges can also be formed by mechanically removing the evaporated film in all but the small area where a bridge is desired.

3) Light mechanical contact between two bulk superconductors. These weak lines may be formed by simply crossing two wires or by screwing a pointed superconducting screw against a bulk superconductor. Here the critical current is determined by the dimensions of the area of contact. The use of a pointed screw allows this area to be adjusted to the desired value after the superconductive quantum interference device is in place in its cryogenic environment.

WHAT WE CLAIM IS:—

1. Apparatus in which:

(a) a device is located in a cryogenic environment to render the device superconducting;

(b) the device comprises a closed superconducting loop which includes at least one

(c) there are no direct electrical connections to the device;

(d) an input circuit inductively coupled to the device induces varying currents in the device of amplitude limited by the critical current of the weak link; and

(d) the varying currents in the device induce output signals in an output circuit inductively coupled to the device.

2. Apparatus as claimed in claim 1 in which a single inductive element inductively coupled to the device, is common to both the input and output circuits.

3. Apparatus as claimed in claim 1 in which the input circuit is shielded from the output circuit by the device.

4. Apparatus as claimed in any one of the preceding claims in which the input circuit and/or the output circuit is or are outside the cryogenic environment.

5. Apparatus substantially as hereinbefore described with reference to and as shown in the accompanying drawings.

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Chartered Patent Agent.

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1,175,091 COMPLETE SPECIFICATION
3 SHEETS

This drawing is a reproduction of the Original on a reduced scale.
SHEET 1

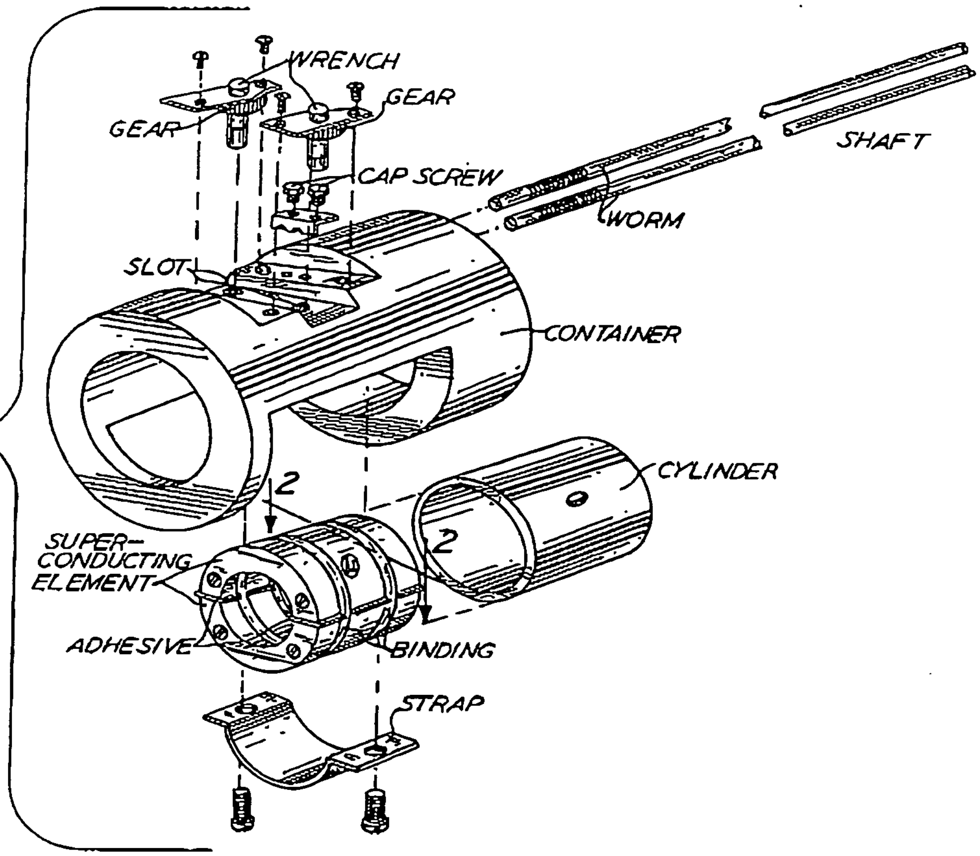


FIG.1

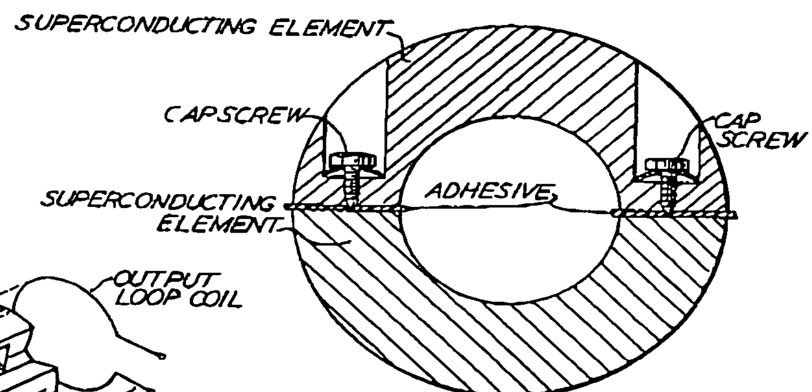


FIG.2

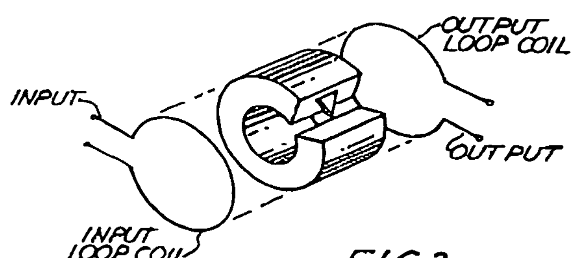


FIG.3

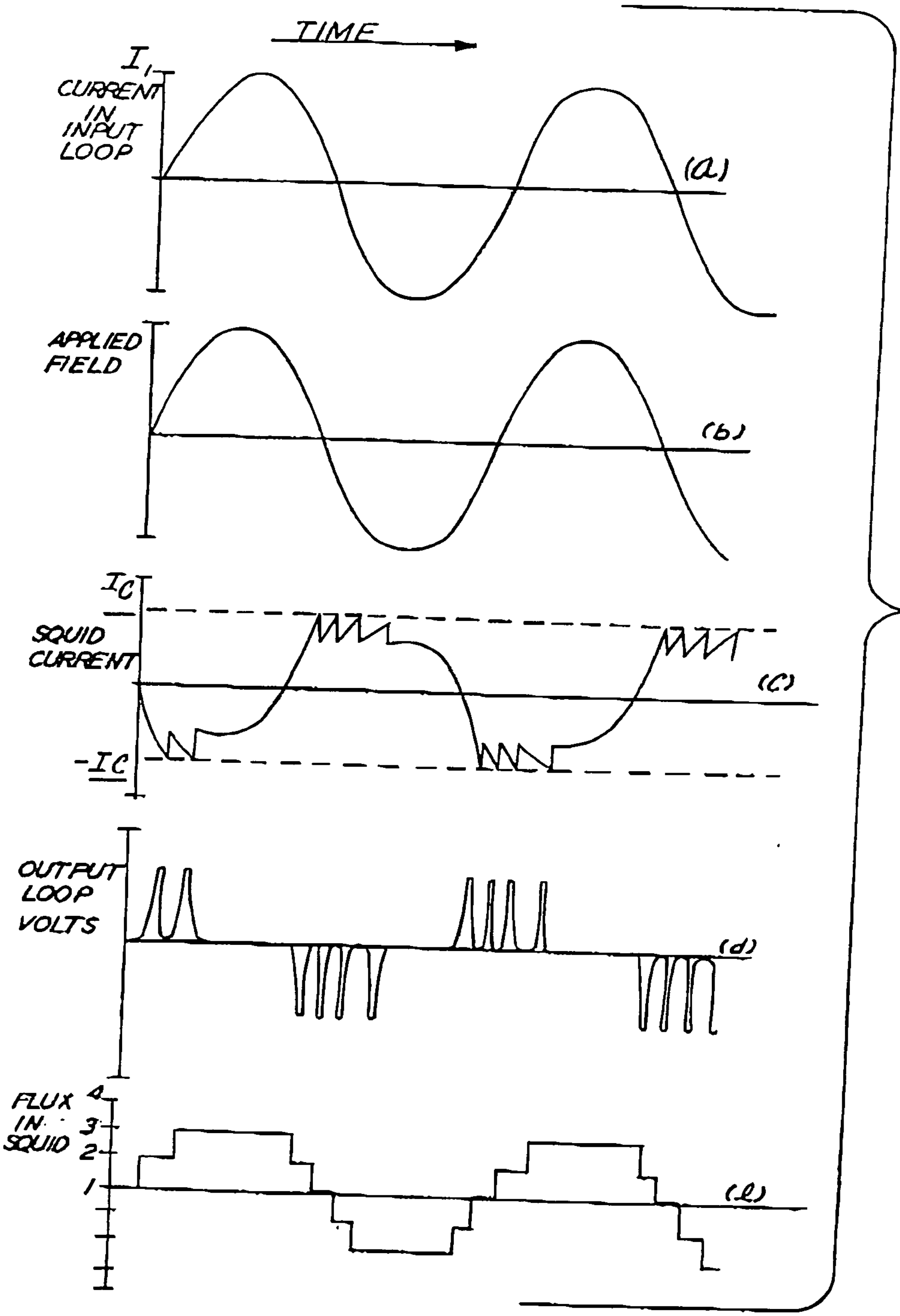

TIME
I_1
CURRENT IN INPUT LOOP
(a)
APPLIED FIELD
(b)
I_C
SQUID CURRENT
(c)
$-I_C$
OUTPUT LOOP VOLTS
(d)
FLUX IN SQUID
4
3
2
1
(e)

FIG. 4

1,175,091 COMPLETE SPECIFICATION
3 SHEETS This drawing is a reproduction of the Original on a reduced scale.
SHEET 3

FIG.5

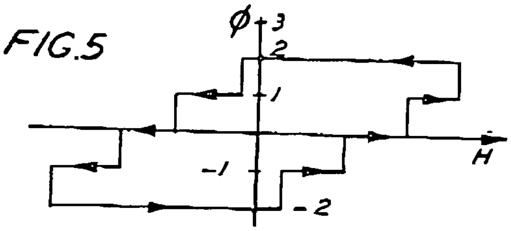
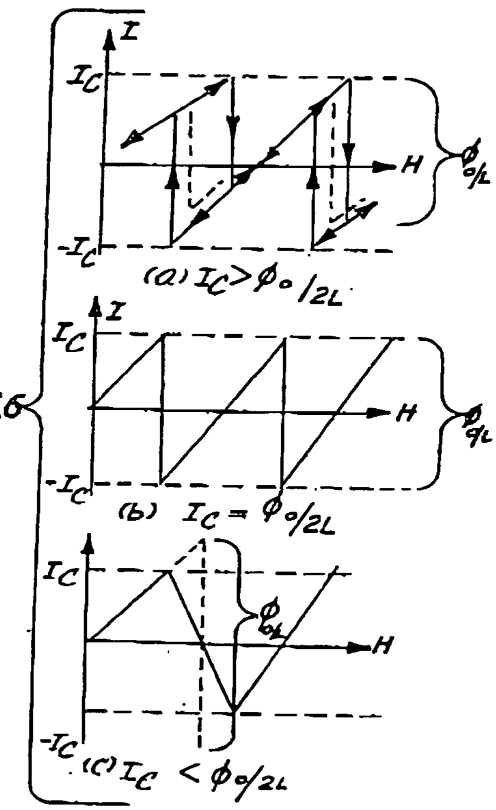


FIG.6



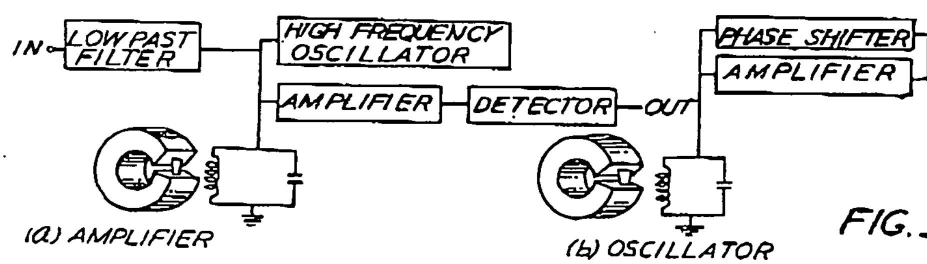


FIG.7